# Flow Augmentation for Dissolved Oxygen Improvement in Chicago Waterways

Emre Alp[1], Charles S. Melching[2], M. ASCE, and Richard Lanyon[3]

[1]Instructor, Department of Environmental Engineering, Middle East Technical University, Ankara 06531, Turkey, PH (+90) 312 210-5853, FAX (+90) 312 210 2646, email: emrealp@metu.edu.tr
[2]Associate Professor, Department of Civil and Environmental Engineering, Marquette University, P.O. Box 1881, Milwaukee, WI, 53201-1881, PH (414) 288-6080, FAX (414) 288-7521, email: charles.melching@marquette.edu
[3]Metropolitan Water Reclamation District of Greater Chicago, 100 E. Erie St., Chicago, IL, 60611-2903, email: richard.lanyon@mwrd.org)

## ABSTRACT

Even though treatment plant (water reclamation plant [WRP]) effluent concentrations meet the applicable standards and most reaches of the Chicago Waterway System (CWS) meet applicable water quality standards, dissolved oxygen (DO) standards are not met in the CWS during some periods. DO deficiencies particularly result in reaches subject to periods of limited flow, such as the upper North Shore Channel (NSC). Thus, an Use Attainability Analysis was initiated to evaluate what water-quality standards can be achieved in the CWS. Flow augmentation practices evaluated for the upper NSC included: i) a portion of the North Side WRP (NSWRP) effluent was transferred to the upstream end of the NSC, ii) the flow was transferred to and divided between two discharge points—one at the upstream end of the NSC and the other at 2.80 km upstream from the NSWRP. It was found that shifting the entire NSWRP effluent flow to the upstream end of the NSC could not achieve 100 percent compliance with a 4 mg/L DO criterion along the upper NSC. Another augmentation alternative was to add oxygen to the NSWRP effluent in the force main, and this transfer of oxygenated effluent was found to effectively improve DO in the upper NSC.

## INTRODUCTION

The Chicago Waterway System (CWS) is composed of the Chicago Sanitary and Ship Canal (CSSC), Calumet-Sag Channel, North Shore Channel (NSC), lower portion of the North Branch Chicago River (NBCR), South Branch Chicago River (SBCR), Chicago River Main Stem, and Little Calumet River (north). The CWS is a 122.8 km branching network of navigable waterways controlled by hydraulic structures in which the majority of flow is treated sewage effluent from 3 of the largest wastewater treatment plants in the world. The dominant uses of the CWS are for commercial and recreational navigation and for urban drainage, i.e. draining combined sewer overflows (CSOs), stormwater runoff, and treated wastewater from the Chicago area away from Lake Michigan, which is the water supply for Chicago. The Calumet and Chicago River Systems are shown in Figure 1.

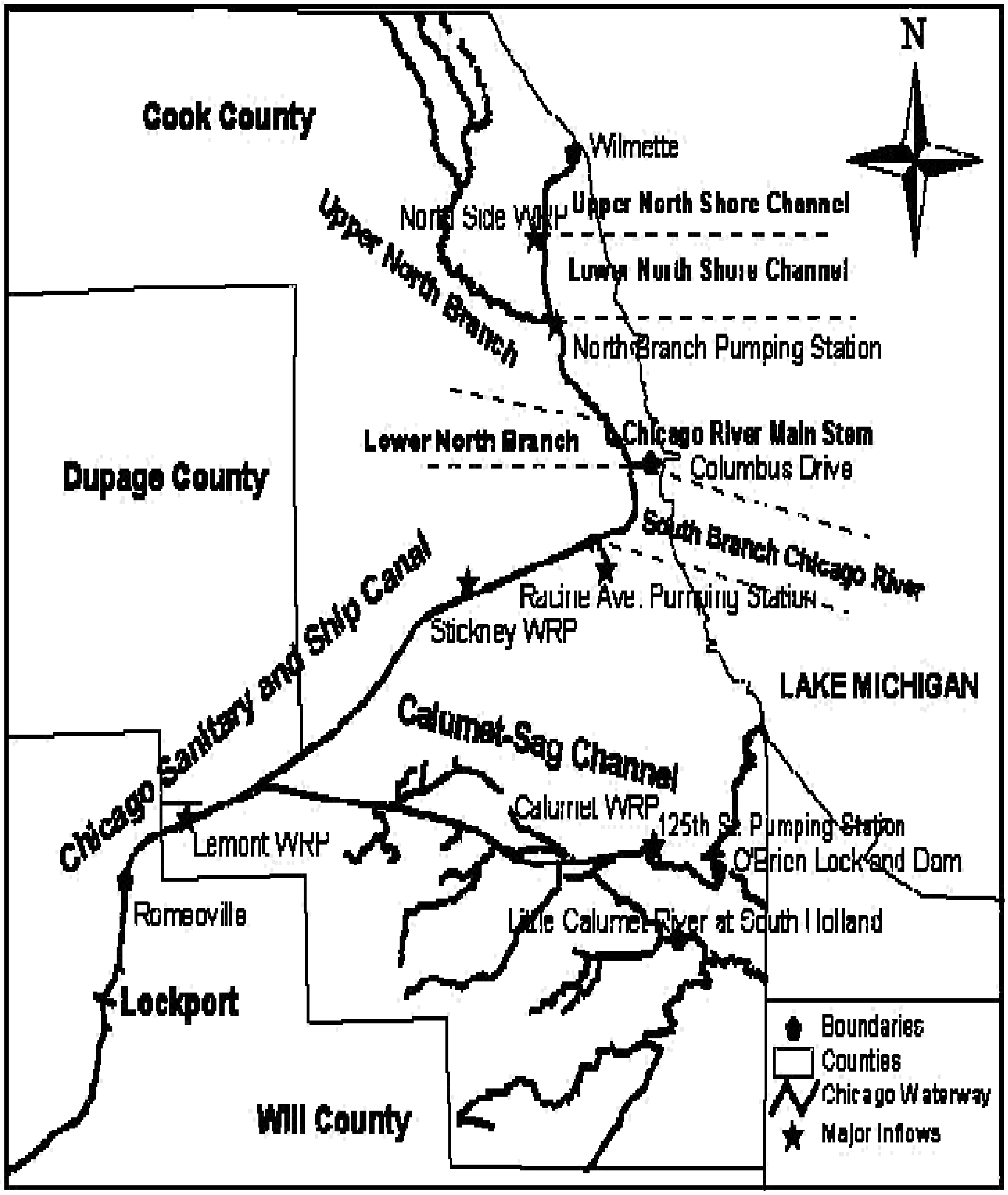


**Figure 1. Schematic diagram of the Calumet and the Chicago River Systems.**

The Illinois Pollution Control Board regulations (Title 35, Section 302.206 and Section 302.405) state that for General Use waters the dissolved oxygen (DO) concentration shall not be less than 6 mg/L during at least 16 hours of any 24 hour period, nor less than 5 mg/L at any time. In the CWS, only the upper NSC and the Chicago River Main Stem are considered General Use waters. The remainder of the CWS is considered Secondary Use waters wherein the DO concentration shall not be less than 4 mg/L at any time except that the Calumet-Sag Channel shall not be less than 3 mg/L at any time. This regulation was established in 1972 with a modification for the Calumet-Sag Channel in 1988, and since that time the Metropolitan Water Reclamation District of Greater Chicago (MWRDGC) has made many improvements to the wastewater treatment plants (water reclamation plants, WRPs), CSOs, and aeration resources of the CWS. Thus, in 2003 the Illinois Environmental Protection Agency initiated an Use Attainability Analysis (UAA) for the CWS to see if DO in the CWS could be brought closer to the General Use standard at a reasonable cost. In anticipation of this UAA and to meet other water-quality management needs the MWRDGC began an intensive sampling of hourly DO and temperature throughout the CWS in 1998, and entered into an agreement with Marquette University in 2000 to develop a water-quality model for the CWS that was suitable for simulating constituent concentrations during unsteady-flow conditions. The DUFLOW (2000) water-quality model developed in the Netherlands was selected for this study for the following reasons.

1) Includes several options for water quality simulation, one that is identical to the WASP4 model of the U.S. Environmental Protection Agency (Ambrose et al., 1988) and another that adds the DiToro and Fitzpatrick (1993) sediment flux model to the WASP formulation.
2) Compatible with Geographical Information Systems.
3) Microsoft Windows based including a powerful graphical user interface.
4) Low license cost.
5) Low computational time.
6) Successfully applied to several European rivers (e.g., Manache and Melching, 2004).

DUFLOW was calibrated and verified for the periods of July 12 to November 9, 2001, and May 1-September 23, 2002, respectively. An extensive data set including hourly in-stream DO data at 25 locations, monthly in-stream water-quality measurements at 18 locations, daily treatment plant effluent measurements, and detailed hydraulic data were used to calibrate and verify the model at a 1-hour output time step. Details of the calibration procedure and results are given in Alp and Melching (2006) and Melching et al. (2004).

The UAA (CDM, 2007) found that although treatment plant effluent concentrations meet the applicable standards and most reaches of the CWS meet the applicable water-quality standards, periods occur when DO standards are not met in the CWS, especially during and after wet-weather periods with CSOs. The upper NSC is particularly prone to low DO concentrations because the flow upstream of the North Side WRP (NSWRP) typically is less than 1 $m^3/s$ during dry weather periods allowing effluent from the WRP to back up into the upper NSC and stagnate because of the low hydraulic gradient throughout the CWS. Further, 21 major gravity CSOs discharge to the upper NSC during storm periods, leaving substantial benthic deposits of organic material. Thus, the UAA (CDM, 2007) recommended that one way to solve the problems related to stagnant/low flow in the upper NSC channel would be to pump a portion of the effluent from the NSWRP 6.6 km to the upstream end of the NSC to create a substantial dry weather flow and to dilute CSO flows such that DO concentrations could be substantially improved. This paper reports the results of different flow augmentation scenarios for the upper NSC.

## SCENARIOS EVALUATED

Three classes of flow augmentation scenarios were evaluated: (1) NSWRP effluent pumped effluent pumped to the upstream end (50%) and to a mid-point (50%) of the upper NSC, and (3) aerated NSWRP effluent pumped to the upstream end of the NSC. The UAA found that reaching the General Use standard would be unrealistic for the upper NSC, and the model was used to determine what would be needed to achieve DO standards of 4, 5, and 6 mg/L. The results for these three cases are summarized in the following sections.

**Flow Augmentation to the Upstream End of the NSC.** For this case two types of flow transfer were considered—the transfer of (1) a fixed amount (2.19 or 4.38 $m^3/s$) and (2) a percentage (10, 50, 75, or 100%) of the NSWRP effluent—for the period July 12–November 9, 2001. The minimum one hour flow from the NSWRP was 4.81 $m^3/s$. Thus, it was necessary to consider a percentage flow transfer rather than a fixed amount transfer to evaluate higher transfer levels. In Alp and Melching (2006) the performance of flow augmentation in improving DO concentrations was considered at two DO monitoring sites on the upper NSC—Simpson Street and Main Street. Main Street generally had lower DO concentrations, and, thus, only results for Main Street are reported in detail here due to space limitations. The percentage of hours that target dissolved oxygen (DO) concentrations of 3, 4, 5, and 6 mg/L are equaled or exceeded for July 12–November 9, 2001 are listed in Table 1 for Main Street. The wet periods listed in the tables in this paper correspond to times when flows at the downstream boundary at Romeoville were higher than typical dry weather flows (i.e. greater than 100 $m^3/s$).

**Table 1. Percentage of time that dissolved oxygen concentrations are higher than the target concentrations at Main Street for July 12 – November 9, 2001 for different transfers of the North Side Water Reclamation Plant effluent**

| | 3 mg/L | | 4 mg/L | | 5 mg/L | | 6 mg/L | |
|---|---|---|---|---|---|---|---|---|
| Scenario | dry | wet | Dry | wet | dry | Wet | dry | wet |
| Measured | 42.8 | 13.8 | 33.7 | 7.7 | 22.9 | 4.4 | 12.5 | 3.0 |
| Calibrated | 47.2 | 22.1 | 36.2 | 15.4 | 19.7 | 6.3 | 9.2 | 0.0 |
| 2.19 $m^3/s$ | 72.0 | 35.2 | 48.3 | 9.6 | 27.0 | 3.8 | 6.1 | 0.0 |
| 4.38 $m^3/s$ | 90.6 | 88.9 | 74.6 | 73.3 | 35.0 | 8.9 | 13.4 | 0.0 |
| 10 % | 61.7 | 28.3 | 41.6 | 7.8 | 24.2 | 0.0 | 5.8 | 0.0 |
| 50 % | 94.8 | 99.7 | 86.0 | 89.1 | 47.3 | 62.9 | 17.9 | 19.0 |
| 75 % | 98.0 | 100.0 | 90.6 | 97.7 | 64.8 | 79.7 | 26.6 | 42.0 |
| 100 % | 98.7 | 100.0 | 94.5 | 99.8 | 74.1 | 87.0 | 31.3 | 49.3 |

The simulation results in Table 1 and Figure 2 show the improvement of DO concentrations in the upper NSC resulting from the flow transfer. It can be seen that even transferring the complete NSWRP flow does not result in attainment of DO concentrations in excess of 3 mg/L at Main Street during dry weather 100 percent of the time. This target DO concentration is achieved 100 percent of the time during wet weather. Surprisingly, for nearly all target DO concentrations and all transfer scenarios higher percentages of compliance are achieved for wet weather than for dry weather. Thus, extra flow for dilution of CSOs is effective in improving DO concentrations in the upper NSC during storms. The simulation results at Addison Street on the NBCR 9.0 km downstream of the NSWRP showed only small decreases in DO concentrations resulting from the transfer because the operation of the Devon Avenue Instream Aeration Station reduces the negative impacts of the flow transfer (Alp and Melching, 2006).

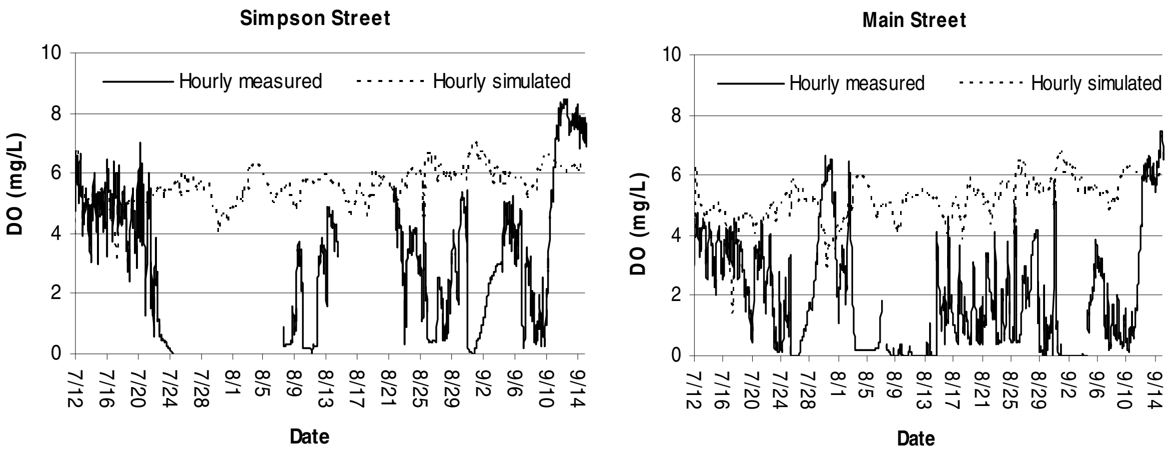


**Figure 2. Simulated hourly dissolved oxygen concentrations at Simpson Street and Main Street on the North Shore Channel for a 100 percent transfer of the effluent of the North Side Water Reclamation Plant to the upstream end of the North Shore Channel compared with measured concentrations for July 12 to September 14, 2001.**

The surprising result that transferring the entire flow from the NSWRP to the upstream end of the NSC does not result in DO concentrations greater than 4 mg/L at all times during dry weather flow is because of two causes. The first is that for most days in July and August 2001 the DO concentration in the NSWRP effluent is 6 mg/L or less (Figure 3). Thus, there is a small margin between the effluent DO concentration and the 4 mg/L target, and the carbonaceous biochemical oxygen demand (CBOD) and ammonia loads and sediment oxygen demand are sufficient to reduce DO concentrations below the 4 mg/L target. The second is that occasionally higher concentrations of CBOD and ammonia are present in the NSWRP effluent. Figure 2 shows the simulated hourly DO concentrations at Simpson Street and Main Street on the upper NSC resulting from a 100 percent transfer of the NSWRP effluent to the upstream end of the NSC for July 12-September 14, 2001. The occasional instances of low DO concentrations are the result of periods with relatively higher CBOD and ammonia concentrations in the NSWRP effluent. For example, on July 17, 2001, the daily mean CBOD and ammonia concentrations in the NSWRP effluent were 10.0 and 3.49 mg/L, respectively (and the daily mean DO concentration was 5.4 mg/L). Whereas, these concentrations are not high relative to the NSWRP permit limitations and general performance of wastewater treatment plants in the U.S., they are more than double and triple, respectively, the CBOD and ammonia concentrations in the NSWRP effluent on most days. Thus, occasional higher concentrations in the effluent, and the small difference between the effluent DO concentration and DO concentration targets means that 100 percent compliance with targets will be difficult to achieve.

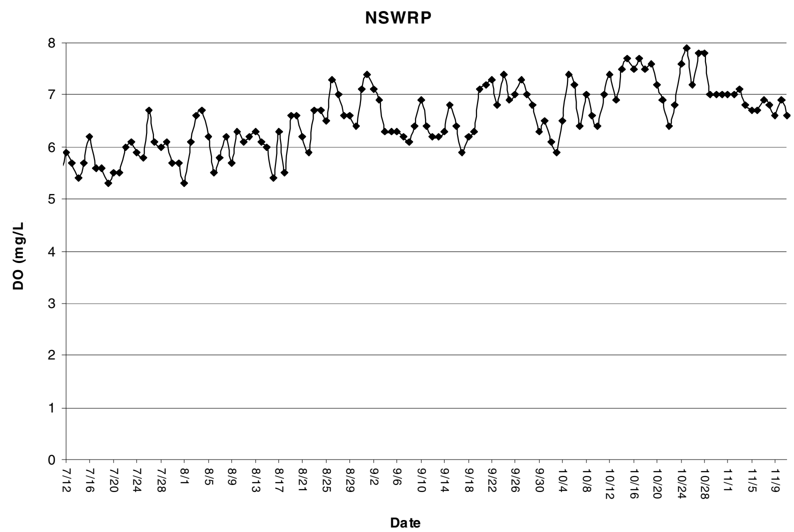


**Figure 3. Daily mean dissolved oxygen concentration in the North Side Water Reclamation Plant Effluent for July 12 – November 9, 2001.**

One final aspect of the results that requires discussion is the reduction in the percentage of the time in compliance with various target DO concentrations when small amounts of effluent (2.19 $m^3$/s or 10 percent) are transferred to the upstream end of the NSC relative to the no transfer (calibrated model) case. For the no transfer case compliance with the various target DO concentrations is achieved at certain times. For some of these times the addition of a CBOD and ammonia load in the transferred effluent may result in a decrease in DO concentrations below the targets. For small flow transfers the number of hours with reduced DO may be greater than the number of hours improved by the effluent transfer. At higher levels of flow transfer, the number of hours improved is substantially more than those that are adversely affected.

**Flow Augmentation with Two Discharge Points.** In this case, the NSWRP effluent is transferred to and divided between two discharge points: one at the upstream end of the NSC and the other 2.80 km upstream from the NSWRP. Again results were obtained for the period of July 12 to November 9, 2001, and the results for Main Street are listed in Table 2.

For flow transfers less than 100 percent, splitting the flow results in slightly worse (a few percentage points less) percentages of compliance with the various target DO concentrations at Simpson Street (Alp and Melching, 2006), but substantially improved percentages of compliance at Main Street. For complete (100 %) flow transfers the results with one or two outlets are nearly identical in terms of percentage of compliance. These results indicate that if a transfer of NSWRP effluent is utilized a final design with multiple outlets would be most efficient as it would yield nearly identical (or even improved) DO concentrations at smaller construction and operation costs.

**Table 2. The percentage of time that dissolved oxygen concentrations are higher than the target concentrations at Main Street on the North Shore Channel for July 12 – November 9, 2001 for different transfers of the North Side Water Reclamation Plant effluent with two discharge points**

| | 3 mg/L | | 4 mg/L | | 5 mg/L | | 6 mg/L | |
|---|---|---|---|---|---|---|---|---|
| Scenario | Dry | Wet | Dry | Wet | Dry | Wet | Dry | Wet |
| Measured | 53.1 | 20.6 | 41.7 | 11.5 | 28.8 | 6.6 | 25.5 | 4.4 |
| Calibrated | 46.7 | 22.1 | 35.7 | 15.5 | 19.6 | 6.3 | 9.2 | 0.0 |
| 4.38 $m^3/s$ | 99.3 | 100.0 | 95.9 | 100.0 | 75.9 | 87.8 | 31.7 | 48.2 |
| 50 % | 99.2 | 100.0 | 95.5 | 100.0 | 76.0 | 87.6 | 31.4 | 49.3 |
| 75 % | 99.1 | 100.0 | 94.9 | 99.9 | 74.9 | 87.6 | 31.3 | 49.5 |
| 100 % | 98.7 | 100.0 | 94.5 | 99.8 | 74.2 | 87.2 | 31.3 | 49.5 |

**Flow Augmentation with Aeration.** It was previously found that even shifting the entire NSWRP effluent discharge to the upstream end of the NSC could not achieve 100 percent compliance with a 4 mg/L DO criterion at Main Street during the period July 12 to November 9, 2001. It was speculated that this resulted because DO concentrations in the NSWRP effluent often were relatively low (between 5 and 6 mg/L) in July and August 2001. The review of aeration technologies by CTE (2007) as part of the UAA alternatives review found that it would be relatively easy to bring the flow to saturation in the force main used to transfer flow from the NSWRP to the upstream end of the NSC. Thus, it was decided to consider a case of flow augmentation wherein oxygen would be added to the NSWRP effluent in the force main.

Daily mean temperature data for the NSWRP effluent for the periods July 12 to November 9, 2001 and May 1 to September 23, 2002 were used to determine the saturation DO concentration in the force main. Some of this DO would be consumed during travel from the NSWRP to the upstream end of the NSC, but this would be matched by a decrease in the CBOD. Thus, for simplicity the quality of the transferred flow was taken as that of the NSWRP effluent with the DO concentration raised to saturation. The transfer amount was taken as the lesser of the selected transfer value or the actual effluent flow for a particular hour.

In the charge to CTE for the NSWRP Facility Plan a target of 90 percent compliance with DO criteria of 4, 5, and 6 mg/L over all flows was set for developing cost estimates. Thus, the aerated transfer amount necessary to meet 90 percent compliance with the DO criteria during the simulated periods is evaluated. The simulated periods are dominated by summer (July-September) conditions during which temperature stresses on DO concentrations are greatest. Thus, 90 percent compliance in the summer implies much higher compliance over an entire year, and the transfer amounts determined are conservative relative to 90 percent compliance over the entire 2 year period. Figure 4 shows the overall percentage compliance with the 4, 5, and 6 mg/L DO criteria resulting from different amounts of flow transfer from the NSWRP to the upstream end of the NSC. Ninety percent compliance with the 4, 5, and 6 mg/L criteria is achieved at Main Street with a transfer of approximately 2.85, 3.94, and 5.69 $m^3/s$, respectively, of aerated effluent (Figure 4). As part of the UAA, CTE (2007) estimated that transferring 4.38 $m^3/s$ of aerated NSWRP effluent to the upstream end of the NSC, where U-tubes (Speece, 1969) are used for aeration, would involve a capital cost of US$60 million and an annual operational cost of US$744,000. The higher flow rate than derived from Figure 4 is necessary to ensure 90% compliance throughout the upper NSC.

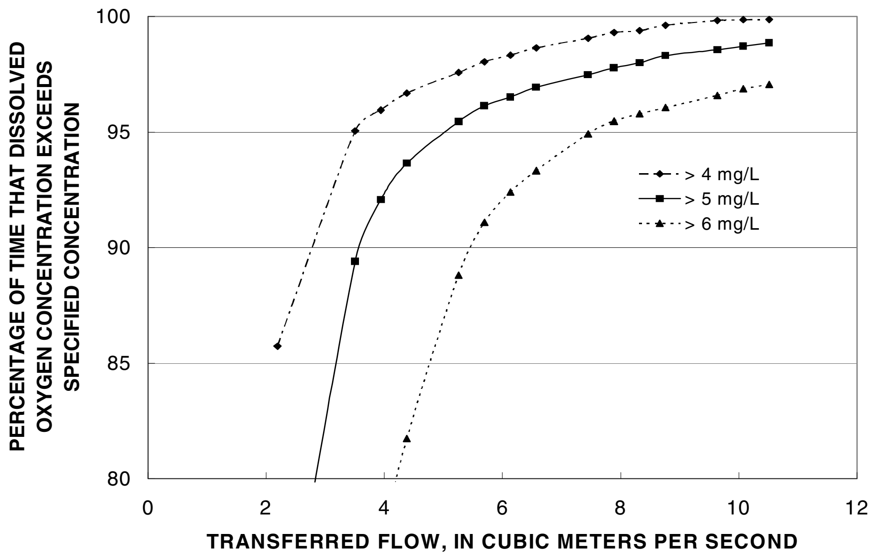


**Figure 4. Relation between aerated North Side Water Reclamation Plant effluent and percentage compliance at Main Street with dissolved oxygen concentration criteria of 4, 5, and 6 mg/L for the periods of July 12-November 9, 2001 and May 1-September 23, 2002.**

The overall percentage compliance with the 4, 5, and 6 mg/L DO criteria resulting from transfer of 3.50, 5.26, 7.45, and 8.32 $m^3/s$ NSWRP flow to the upstream end of the NSC at the locations downstream from NSWRP are shown in Tables 3 and 4. Even though the increase in DO is not as drastic as that observed along the NSC, at least 10% improvement is achieved by transferring 8.32 $m^3/s$ compared to 3.50 $m^3/s$ at Addison Street, 9.0 km downstream from the NSWRP, for the 6 mg/L DO criterion (Table 3). The DO criterion of 5 mg/L could be met 95 and 94.1 percent of the time for dry and wet weather periods, respectively, at Addison Street by a transfer of 3.50 $m^3/s$. However, even a transfer of 8.32 $m^3/s$ aerated NSWRP flow could not result in 90 % compliance with a 5 mg/L criterion at Fullerton Avenue, 12.1 km downstream from the NSWRP (Table 4).

Thus, additional instream aeration stations would be needed to achieve 90% compliance with a 5 mg/L DO standard on the NBCR downstream from Addison Street. Results show that the effect of flow augmentation with aeration decreases considerably at locations downstream from the junction of the NBCR and SBCR (Alp and Melching, 2006).

**Table 3. The percentage of time that dissolved oxygen (DO) concentrations are greater than the target concentrations at Addison Street on the North Branch Chicago River for July 12-November 9, 2001 and May 1-September 23, 2002 for different transfers of North Side Water Reclamation Plant effluent brought to saturation DO concentration.**

| | >4 mg/L | | >5 mg/L | | >6 mg/L | |
|---|---|---|---|---|---|---|
| Scenario | Dry | Wet | Dry | Wet | Dry | Wet |
| Baseline | 99.0 | 99.8 | 89.9 | 91.3 | 55.4 | 62.2 |
| 3.50 $m^3/s$ | 99.6 | 99.8 | 95.0 | 94.1 | 68.8 | 67.2 |
| 5.26 $m^3/s$ | 99.6 | 99.7 | 96.6 | 94.9 | 74.2 | 71.0 |
| 7.45 $m^3/s$ | 99.7 | 99.7 | 97.7 | 96.4 | 81.5 | 75.6 |
| 8.32 $m^3/s$ | 99.8 | 99.7 | 98.1 | 96.8 | 83.9 | 78.3 |

**Table 4. The percentage of time that dissolved oxygen (DO) concentrations are greater than the target concentrations at Fullerton Avenue on the North Branch Chicago River for July 12-November 9, 2001 and May 1-September 23, 2002 for different transfers of North Side Water Reclamation Plant effluent brought to saturation DO concentration.**

| | >4 mg/L | | >5 mg/L | | >6 mg/L | |
|---|---|---|---|---|---|---|
| Scenario | Dry | Wet | Dry | Wet | Dry | Wet |
| Baseline | 89.5 | 95.5 | 54.1 | 72.3 | 18.6 | 38.6 |
| 3.50 $m^3/s$ | 93.8 | 95.8 | 70.2 | 80.3 | 28.6 | 46.7 |
| 5.26 $m^3/s$ | 96.2 | 96.0 | 75.5 | 84.1 | 32.3 | 49.5 |
| 7.45 $m^3/s$ | 97.5 | 96.8 | 79.6 | 86.7 | 41.5 | 54.3 |
| 8.32 $m^3/s$ | 97.9 | 97.2 | 81.2 | 87.5 | 44.7 | 56.9 |

## CONCLUSIONS

Simulation of the period July 12-November 9, 2001 with the DUFLOW model calibrated and verified for the CWS found that transfer of even the entire flow from the NSWRP to the upstream end of the NSC would not result in 90% compliance with the 5 mg/L DO criterion. Splitting the transferred effluent between the upstream end of the NSC and a point 2.80 km upstream of the NSWRP yielded similar results to the case of transferring all the flow to the upstream end of the NSC at a potentially reduced cost. Aeration of the transferred effluent in the force main was found to be an effective and efficient means to improve the DO concentrations to acceptable levels (5 mg/L, 90% of the time) in the upper NSC with estimated construction and operation costs of US$ 60 million and 744,000/year, respectively. The benefits of this aeration also allow compliance with target DO criteria for about 10 km downstream of the NSWRP, whereas, compliance further downstream will require supplemental aeration stations.

Refined design of the flow augmentation for the upper NSC channel is currently under study as part of the development of an integrated strategy for water quality improvement throughout the CWS. This design will test flow augmentation performance against new dissolved oxygen standards proposed by the Illinois Environmental Protection Agency for selected representative wet and dry years for the CWS. Single and multiple discharge points for the transferred flow will be considered. Combination of the aerated flow augmentation with addition of instream aeration stations will also be considered.

## REFERENCES


Alp, E. and Melching, C.S. (2006). Calibration of a model for simulation of water quality during unsteady flow in the Chicago Waterway System and application to evaluate use attainability analysis remedial actions. *Technical Report 18*, Institute of Urban Environmental Risk Management, Marquette University, Milwaukee, WI.

Ambrose, R.B., Wool, T.A., Connolly, J.P., and Schanz, R.W. (1988). WASP4, a hydrodynamic and water quality model—model theory, User's manual, and programmer's guide. U.S. Environmental Protection Agency, *EPA/600/3-87-039*, Athens, GA.

Camp Dresser and McKee (CDM), 2007, Chicago Area Waterway System Use Attainability Analysis (UAA), report submitted to the Illinois Environmental Protection Agency, available on line at http://www.chicagoareawaterways.org/documents/CAWS-UAA-Final-Report.pdf.

Consoer Townsend Envirodyne (CTE), 2007, Flow Augmentation of the Upper North Shore Channel, *Technical Memorandum 5WQ*, report submitted to the Metropolitan Water Reclamation District of Greater Chicago, Chicago, Ill.

Di Toro, D. M. and Fitzpatrick, J. (1993). *Chesapeake Bay Sediment Flux Model*. HydroQual, Inc. Mahwah, NJ. Prepared for U.S. Army Engineer Waterway experiment Station, Vicksburg, MS. Contract Report EL-93-2

DUFLOW (2000). *DUFLOW for Windows V3.3: DUFLOW modelling studio: user's guide, reference guide DUFLOW, and reference guide RAM*, EDS/STOWA, Utrecht, The Netherlands.

Manache, G. and Melching, C.S. (2004). Sensitivity analysis of a water-quality model using Latin hypercube sampling. *Journal of Water Resources Planning and Management*, **130**(3), 232-242.

Melching, C.S., Alp, E., Shrestha, R.L., and Lanyon, R. (2004). Simulation of water quality during unsteady flow in the Chicago Waterway System. *Proceedings CD-ROM*, *Watershed 2004*, July 11-14, 2004, Dearborn, MI, Water Environment Fedaration.

Neugebauer, A. and Melching, C.S. (2005). Verification of a continuous water quality model under uncertain storm loads in the Chicago Waterway System, *Technical Report 17*, Institute of Urban Environmental Risk Management, Marquette University, Milwaukee, WI.

Speece, R. (1969). U-tube stream reaeration, *Public Works*, 100, 111-113.